FACILITIES FOR SIMULATING COMBINED CONVECTIVE AND RADIATIVE ENTRY-HEATING ENVIRONMENTS

By Forrest E. Gowen,* John H. Lundell,* and Bradford H. Wick

Ames Research Center, NASA, Moffett Field, California, 94035

ABSTRACT

This paper describes facilities developed by NASA-Ames Research Center for investigating ablative heat-shield materials for manned vehicles that will encounter both convective and radiative heat fluxes during entry into the Earth's atmosphere. The general design and performance of the facilities are described, and the performance is related to entry heating conditions expected for manned lunar return (Apollo) and Mars return vehicles. The possible application of the facilities to planetary entry problems is briefly considered.

Three facilities have been developed which provide different ranges of heating conditions and sizes of ablation specimens. The same general design concept was used for the facilities. An arc-heated, high-speed gas jet is used in each facility to provide the convective heating conditions, and the radiative fluxes are provided by a combination of an electric-arc radiation source (or sources), and an optical system for collecting and focusing the radiation. One facility is in use, the second is nearing completion, and the third is in the initial stages of construction. The first facility provides convective and radiative fluxes that are somewhat higher than those expected for the normal entry conditions for the Apollo vehicle, but the facility is limited to small specimen sizes (less than one-half inch diameter for radiative targets) and modest arc jet conditions. The second facility was developed to provide combined heating on specimen sizes up to four inches in diameter using arc heaters with increased enthalpy and total pressures, without sacrificing model flux levels. The third facility will provide radiative and convective flux levels, and arc-jet conditions approaching those expected for a manned Mars return vehicle; specimen size is intermediate to those of the other two facilities.

INTRODUCTION

Vehicles entering planetary atmospheres can encounter both convective and radiative heating of considerable magnitudes. (See, e.g., refs. 1-4.) Therefore, heat shield materials for these vehicles must be designed and tested to insure vehicle survival. In order to test the materials, ground-based facilities must be developed to duplicate the heating environments, or if this is not feasible, then to simulate the environments.

In this paper, facilities which are used for simulation of combined convective and radiative entry-heating environments will be discussed briefly. First, the requirements for these facilities and some of the limitations imposed upon simulation of these heating fluxes in ground-based facilities will be discussed. Next, the combined heating facilities developed at Ames Research Center will be described and their performance given. Last, the expected performance capabilities of possible future facilities will be discussed.

SIMULATION REQUIREMENTS

In order to discuss the requirements for simulation consider first the entry environment shown in figure 1. For the purpose of this paper only the stagnation region of a vehicle entering the atmosphere at a velocity, V, and density, ρ, will be considered. The velocity and density are such that a high temperature gas cap is formed which will provide both convective heating (due to flow of the hot gases over the vehicle surface) and radiative heating (due to radiation from the high temperature gases within the gas cap). For example, the flight environment for peak heating during an Apollo entry at about 12 km/sec is tabulated in the figure. For this velocity an impact pressure of about 0.6 atm and stagnation-region temperature of about 9600° K are developed. It would be preferable to test full-scale models at velocities and densities (or impact pressures) for the full-scale vehicles. However, this is generally not feasible in a ground-based facility, and, as a result, we must simulate full-scale heating environments rather than duplicate them.

PARAMETERS

In this simulation, consider the significant simulation parameters for the entry-heating environment. The first two of these are given by the following relations

$$h_t \sim V^2$$

$$p_t \sim \rho V^2$$

where h_t is the stagnation enthalpy and p_t is the impact pressure at the vehicle surface and ρ and V are the free-stream density and velocity, respectively. The third parameter is vehicle size, or nose radius. Since these parameters may vary with time in the flight environment, time must be included in the list of parameters for proper simulation. Our ground-based facilities must provide a wide enough range of these parameters to allow an understanding of the material ablation process to be developed along with theoretical and semiempirical methods for predicting the flight performance of the heat-shield material.

The stagnation-point heating results from a combination of convective heating, radiative heating and a combustion of gases and surface material. Details of these processes are beyond the scope of this paper and can be found in references 2, 5, and 6. Only the simple equations for laminar-convective and equilibrium-radiative heating will be discussed here. (See refs. 7 and 8.) Consider first the convective heating in the stagnation region of a hemispherical body. It can be expressed as follows:

*R

(NASA-TM-X-74456) FACILITIES FOR SIMULATING COMBINED CONVECTIVE AND RADIATIVE ENTRY-HEATING ENVIRONMENTS (NASA) 5 p

N77-74202

Unclas

00/98 30060

$$\dot{q}_c \cong \text{constant} \cdot \sqrt{\frac{p_t}{R_n}} \cdot h_t \qquad (1)$$

where p_t is the model impact pressure, R_n is the nose radius, and h_t is the stagnation enthalpy.

Generally, for economic or technical reasons the laboratory model size or nose radius is much smaller than for full-scale vehicles. However, equation (1) indicates that either enthalpy or pressure can be varied to compensate for the small model nose radius. If we reproduce flight values of enthalpy in the laboratory environment, the impact pressure may be reduced below the flight value in order to reproduce full-scale heating on small scale models. Thus, a full-scale convective heating environment can be reproduced over a considerable range of parameters in the laboratory.

Unfortunately, the radiative flux cannot be adjusted in the manner described for the convective flux. This fact is demonstrated by the following equation which is an approximate expression for the stagnation-point radiative flux:

$$\dot{q}_r \cong \text{constant} \cdot p_t^{1.8} h_t^{m} R_n \qquad (2)$$

where m varies from 1 to about 5. It is apparent from this expression that the radiative heating rate varies directly with nose radius. Thus a reduction from full scale to model size (a reduction of as much as 100 to 1) results in greatly reduced radiative heating rates even if flight enthalpy and pressure are matched. A solution to this scaling problem is to irradiate the model with an external source.

Representative Flight Heating Rates

In order to provide an appreciation for the orders of magnitude of the convective and radiative heating fluxes imposed upon flight vehicles, stagnation-point rates for three different manned missions are given in figure 2. These are, a satellite mission such as Gemini, an Apollo-type mission and the reentry into the Earth's atmosphere from a manned Mars mission. For the satellite entry, the stagnation-point heating is essentially all convective and less than 60 W/cm^2. For Apollo vehicles, the convective heating is about 300 W/cm^2 and the radiative heating rate is about 700 W/cm^2. For the Mars return mission, both the convective and radiative heating rates are almost one order of magnitude higher than those for the Apollo vehicle. Thus, with current and future missions, stagnation-point heating rates vary over almost two orders of magnitude.

With this background discussion on some of the convective and radiative heating requirements and some of the important simulation parameters, we will next consider the facilities at Ames Research Center which are used to provide combined-heating environments.

AMES ENTRY-HEATING FACILITIES

Entry-Heating Simulator

The facility is shown in figure 3. It is described in detail in reference 8. This facility provides independent control over the radiative and convective heating rates. The convective heating flux is provided by a combination of an Ames developed arc heater with a contoured nozzle. (See ref. 9.) The radiative heating flux is obtained from an arc-imaging system utilizing a 22 kW carbon arc which is placed at the focal point of an ellipsoidal mirror. This arc is then reimaged on the model which is placed at the focal point of a second ellipsoidal mirror. The resulting radiation has a spectral distribution that is largely within the visible and infrared range.

Figure 4 shows the convective heating rates that are available in the Entry Heating Simulator with various model impact pressures. Also shown by the dashed lines are the corresponding values of stagnation enthalpy. In the table at the right is shown a comparison of the convective heating performance of this facility and two mission requirements. It is apparent that the convective heating rate for the Apollo can be matched, but that for the Mars return mission cannot. The other parameters cannot be matched for either mission.

The radiative heating fluxes available in this facility are shown in figure 5. This figure indicates the gaussian type of radiation flux distribution that is imposed upon the model. This nonuniform distribution results from the use of the simple ellipsoidal-mirror optical system and the nonuniform carbon arc source of finite size. With this distribution the test area on the model is limited to a diameter of about 0.8 cm. The maximum radiative heating flux is about equal to the peak value shown for the Apollo, and about 1/8 that for the Mars return mission.

The convective and radiative heating rates provided by the facility are sufficiently high that some materials can be evaluated and some fundamental understanding of their ablation processes can be obtained. Model sizes are too small, however, for the proper evaluation of the performance of modular types of heat-shield materials such as filled honeycomb materials. It was this shortcoming in model size as well as the poor radiative flux distribution available that led to a larger facility which is designated the Ames Combined Heating Facility and is described below.

Combined Heating Facility

Figure 6 is a schematic view of the facility which shows the convective heating system and two modules of the 14-module radiative heating system. This facility was designed to provide uniform radiative and convective heating fluxes over material samples as large as 10 cm in diameter with independent, time-variable control over both radiative and convective heating fluxes.

Convective Heating System

The system was designed to use different arc heaters, because no single heater is available to cover the entire pressure-enthalpy spectrum desired. With this design, more advanced arc heaters can be installed, with very little facility modification. Two arc heaters are currently used for this facility. These are a high-pressure, moderate-enthalpy heater and a low-pressure, high-enthalpy heater. The high-pressure arc heater is a Linde Company design which is described in detail in the literature and will not be discussed here. (See refs. 10, 11, and 12.) The high-enthalpy arc heater is a constricted-arc type similar to the heaters described in considerable detail in a paper presented by Mr. Charles Shepard and will not be described here. (See refs. 13, 14, 15, and 16.) The references for the convective arc heaters discuss in considerable detail the various factors limiting arc heater performance and, therefore, the convective heating system performance.

Radiative Heating System

Each module of this system consists of an Ames 125 kW radiation source (ref. 17) with its collector, a field lens, a folding mirror and a combination projection lens and a test chamber window. The collector was designed to make the distribution of radiative flux on the field-lens plane as uniform as possible. The projection lens reimages this field-lens flux distribution upon 10-cm diameter flat-faced models. The folding mirror was included to reduce the size of the system. In addition to these main components, each module contains a water filter, uniformity filter, and a douser located between the field lens and the folding mirror. The douser is used to intercept the radiative flux while the system is being started and brought to the desired operating condition. The projection lenses for the 14 modules are equally spaced around the center line of the arc heater and nozzle. An estimate of the overall size of the facility can be obtained from the overall length of the optical system which is a little over 5 meters long, and the test box height which is about 2 meters. Although not shown here, the entire optical path around the test chamber is enclosed within an air-conditioned structure. This is necessary to protect personnel from the ultraviolet radiation and ozone produced, and to protect the components of the system from dust and ozone.

Performance of Combined Heating Facility

Convective heating system.- Figure 7 shows the model impact pressures and stagnation-point convective heating rates available in this facility using the two arc heaters previously discussed. The test region results from a combination of the test regions available with both arc heaters. The operating limits were estimated from actual operational data obtained on the arc heaters corrected to the nozzle area ratio and model effective nose radius for this facility. The corresponding values of stagnation enthalpy are shown by the dotted lines. The table shows that the convective heating rate and the enthalpy for the Apollo mission can be matched; however, the impact pressure is too low. It should be noted that if a smaller nozzle exit diameter (and hence smaller model) were used, the Apollo heating rates, enthalpy and impact pressure could be matched.

Radiative heating system.- In order to estimate the performance of the radiative heating system one prototype module of the 14-module radiative heating system was assembled and its performance measured. The data taken on this single module then were adjusted for the 14-module operation of the Combined Heating Facility. The results are presented in figure 8. Shown here is the maximum unfiltered flux distribution that is expected for a 10-cm-diameter model. The approximate area-average heating rate is about 680 W/cm^2. This is only slightly below the value shown for the Apollo vehicle.

The flux distribution is altered when uniformity and water filters are added to each module. The uniformity filter will remove part of the energy in the central region of the distribution, and reduce the level of the area-average flux to about 400 W/cm^2 with a flux variation of only ±5 percent.

FUTURE FACILITY DEVELOPMENT

The performance of the Combined Heating Facility shown in figures 7 and 8 as well as the performance of the Entry Heating Simulator given in figures 4 and 5 are considerably below that required for missions such as the manned Mars return; hence, more advanced facilities need to be developed.

Work currently in progress is expected to provide, by 1968 and 1972, the capabilities shown in Table I. For comparison the Mars return mission is also listed. The 1968 facility is an advanced version of the Entry Heating Simulator. Note that its performance will still be short of that required for the mission shown. However, by 1972, it will be possible, with small models, to match all the listed performance requirements except for impact pressure. Note that for larger models, the 1972 performance will still be considerably below the mission requirements.

The 1968 Advanced Entry Heating Simulator performance is based upon the present day state-of-the-art for both the arc heater and the radiation source. The only serious performance limitation of the facility is the low radiative heating rate compared to the Mars mission requirement. This limitation results from the requirements (1) that the optical system provide a uniform flux distribution on the model, and (2) that it incorporate only one of the recently developed Ames 125 kW radiation sources. Even with this source, the power and radiance are not high enough to attain the radiative heating rate for the Mars mission.

As a result of the radiation source performance limitation, Ames Research Center has sponsored a development program with Electro-Optical Systems, Inc. The goals for this source development are an increase in available source output power by a factor of about 5 and an increase in average radiance by a factor of 3 to 4. Early results from prototype tests indicate that the radiance goal can be obtained, and that input powers in excess of 1 megawatt are practical. However, the operating efficiency may be only 10 to 20 percent. Development of this source is not expected to be completed before 1968. The use of this future radiation source along with an advanced constricted-arc heater would provide the performance capability shown in the "1972 state-of-the-art" column for the small model. The possible 1972 performance capabilities shown for the larger model size was estimated using a 30 megawatt constricted-arc heater to provide the convective flux and a number of the 1 megawatt radiation sources to provide the radiative flux.

CONCLUSIONS

It has been shown that convective and radiative heating environments of missions such as the Gemini and Apollo missions can be simulated using existing convective arc heaters and radiation sources.

However, to simulate the entry heating environment for missions such as the manned Mars return, considerable development of both convective and radiative heating systems must done if models as large as 10 cm in diameter are to be tested.

REFERENCES

1. Demele, Fred: A Study of the Convective and Radiative Heating of Shapes Entering the Atmospheres of Venus and Mars at Superorbital Speeds. NASA TN D-2064, 1963.

2. AIAA Entry Technology Conference: Williamsburg and Hampton, Va., Oct. 12-14, 1964, AIAA Pub. CP-9.

3. Study of Heat Shielding Requirements for Manned Mars Landing and Return Missions. Rep. No. 4-74-64-1, Lockheed Missiles and Space Company, Sunnyvale, Calif., Dec. 1964.

4. Seiff, Alvin, and Tauber, Michael E.: Minimization of the Total Heat Input for Manned Vehicles Entering the Earth's Atmosphere at Hyperbolic Speeds. NASA TR R-236, 1966.

5. Lundell, John H., Wakefield, Roy M., and Jones, Jerold W.: Experimental Investigation of a Charring Ablative Material Exposed to Combined Convective and Radiative Heating. AIAA J., vol. 3, no. 11, Nov. 1965, pp. 2087-2095.

6. Vojvodich, Nick S., and Pope, Ronald B.: Effect of Gas Composition on the Ablation Behavior of a Charring Material. AIAA J., vol. 2, no. 3, March 1964, pp. 536-542.

7. Lees, Lester: Recovery Dynamics - Heat Transfer at Hypersonic Speeds in a Planetary Atmosphere. Space Technology, Chap. 12, Howard Seifert, ed., John Wiley and Sons, New York, N. Y., 1959, pp. 12-01-12-20.

8. Lundell, John, Winovich, Warren, and Wakefield, Roy M.: Simulation of Convective and Radiative Entry Heating. Second National Symposium on Hypervelocity Techniques, Denver, Colorado, March 19 and 20, 1962.

9. Gowen, Forrest, and Hopkins, Vaughn: A Wind Tunnel for Using Arc Heated Air for Mach Numbers from 10 to 20. Second National Symposium on Hypervelocity Techniques, Denver, Colorado, March 19 and 20, 1962.

10. Eschenbach, R. C., Skinner, G. M., et al.: Development of Stable High Power High Pressure Arc Air Heaters for a Hypersonic Wind Tunnel. WADD Tech. Rep. 61-100, July 1961.

11. Smith, Richard T., and Kachel, Werner A.: Design and Performance of a High Pressure Continuous Flow Arc Heater. AFFDL TR-66-48, May 1966.

12. Sarlitto, R. J., Eschenbach, R. C., Bryson, D. A., Laakaniemi, R. H., and Troue, H. H.: Development of High Enthalpy, High Power Arc Air Heaters. RTD-TDR-63-4055, Linde Company, Indianapolis, Indiana, Feb. 1964.

13. Shepard, C. E., and Watson, V. R.: Performance of a Constricted-Arc Discharge in a Supersonic Nozzle. Fifth Biennial Gas Dynamics Symposium, Northwestern University, Technological Institute, Aug. 14-16, 1963.

14. Stine, Howard A.: The Hyperthermal Supersonic Aerodynamic Tunnel. Proc. High Temperature Technology, Asilomar, Pacific Grove, Calif., Sept. 8, 1963, Butterworth, 1964.

15. Vorreiter, J. W., and Shepard, C. E.: Performance Characteristics of the Contricted-Arc Supersonic Jet. Proc. 1965 Heat Transfer and Fluid Mechanics Institute, Stanford University Press, 1965.

16. Shepard, Charles E., Ketner, Donald M., and Vorreiter, John W.: A High Enthalpy Plasma Generator for Entry Heating Simulation. 13th Annual Institute of Environmental Sciences Technical Meeting and Equipment Exposition, Washington, D. C., April 10-12, 1967.

17. Sorensen, Carl, and Camacho, Salvador: Experimental Results of Radiation Source Development by Ames Research Center. AIAA Preprint 66-185, 1966.

TABLE I.- FUTURE CAPABILITIES

PARAMETER	MARS RETURN MISSION	1968 FACILITY	1972 STATE OF ART	
			SMALL MODEL	LARGE MODEL
$\dot{q}_c$, W/cm²	3500	5000	~8200	~2000
$\dot{q}_r$, W/cm²	5500	2000	~8500	~2700
p_t, atm	1.9	.5	1.0	.5
h_t, MJ/kg	92	~ 100	~100	~100
$R_{n, eff}$, cm	30.4	1.9	1.9	~20

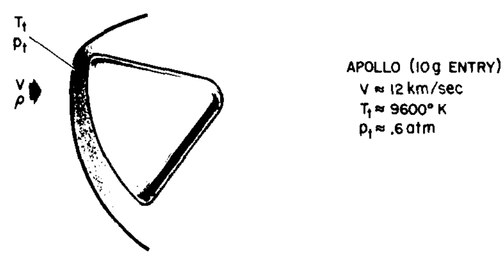

Figure 1.- Entry heating environment.

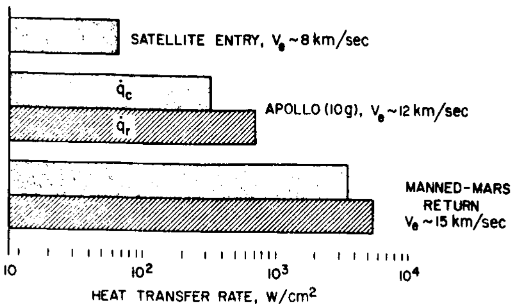

Figure 2.- Maximum heat-transfer rates for manned entry vehicles.

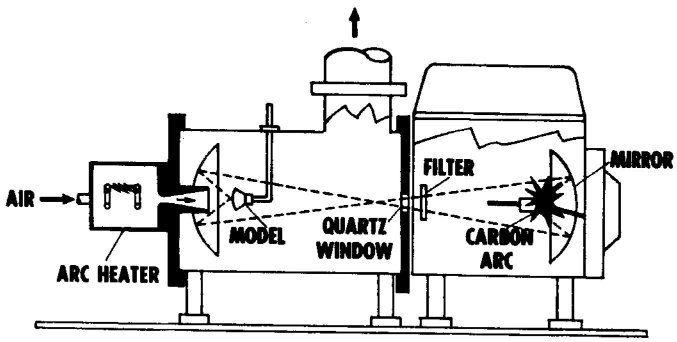

Figure 3.- Ames Entry-Heating Simulator.

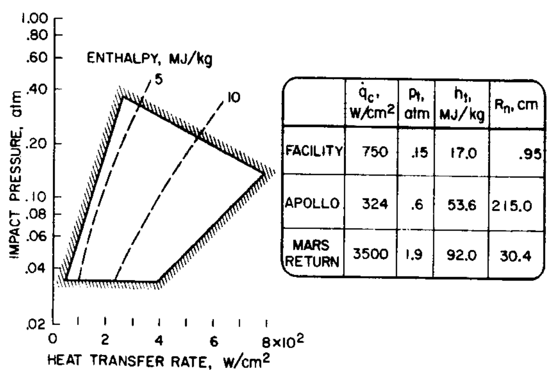

Figure 4.- Convective-heating performance of the Ames Entry-Heating Simulator.

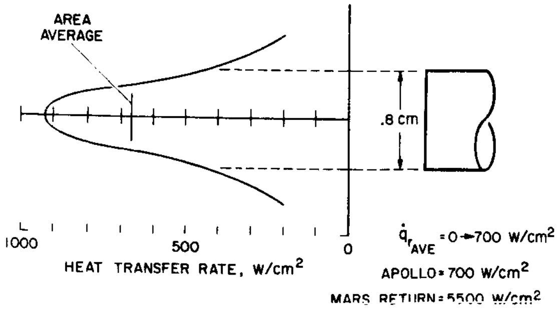

Figure 5.- Radiative heat-transfer distribution for the Ames Entry-Heating Simulator.

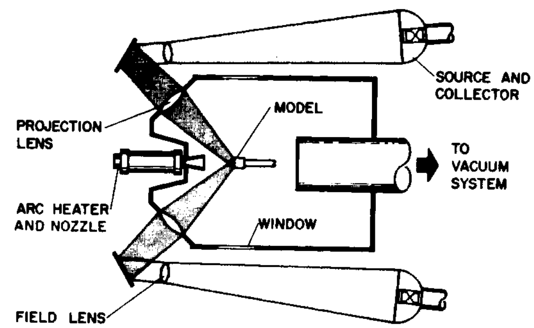

Figure 6.- Ames Combined-Heating Facility.

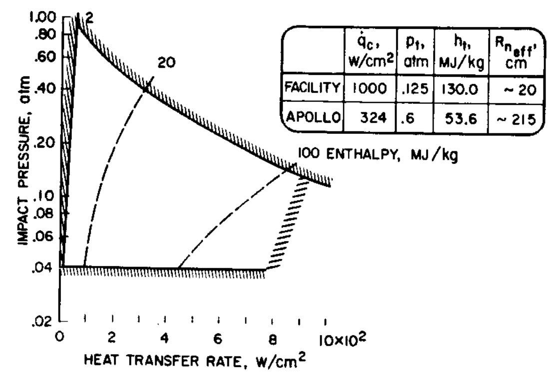

Figure 7.- Convective heating performance of the Ames Combined-Heating Facility.

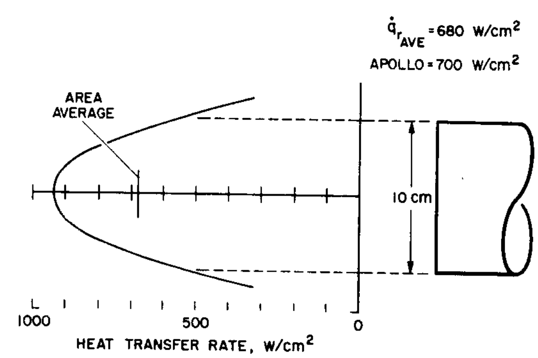

Figure 8.- Expected radiative heat-transfer distribution for the Ames Combined-Heating Facility.